Tidal Eddy Generation at Three Tree Point: Theory and Numerical Modeling

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Abstract
Results are presented from a 3-D numerical simulation of flow near Three Tree Point, in the Main Basin of Puget Sound, Washington. The model uses realistic bathymetry and stratification in a small section of Main Basin, and is forced with typical tidal currents. Interaction of the tidal flow with Three Tree Point is found to give rise to long-lived headland eddies, which are an effective mechanism for horizontal tracer dispersion. In addition, strong internal lee waves are forced in deeper water near the Point, with vertical isopycnal displacements of up to 50 meters.

Introduction
The mixing and dispersion of salinity, nutrients, and pollution in coastal and estuarine waters is largely controlled by the interaction of tidal currents with irregular bathymetry. These interactions can be extremely complex, and numerical modeling has proven to be an effective tool for understanding some of the important properties. In shallow water, tidal residual flow, particularly near headlands and straits, can cause large effective horizontal diffusivity in localized regions (Zimmerman 1981; Ridderinkhof and Zimmerman 1992; Signell and Geyer 1990, 1991). However, these tidal residuals have mostly been studied in shallow water, where the frictional spin-down time is short compared with the tidal period. This tends to organize the tidal dispersion in predictable patches within a tidal excursion of the headland. In deeper water, two new physical processes may occur (MacCready and Pawlak 2001). First, the headland eddies may last for several tidal periods, allowing eddy interaction, and potentially spreading the stirring zone farther in space. Second, stratified flow may choose to go either over or around the sloping ridge. If it goes around (as it does for slower flow) then classical headland eddies result. If it goes over (as for faster flow) then the flow response may be more baroclinic, with lee waves in the density field, and possibly with significant turbulent mixing.

Numerical Model Setup
To study tidal headland eddy dynamics in a realistic situation we will use Three Tree Point in the Main Basin of Puget Sound, Washington (Figure 1). This is a sharp feature on the coastline, with cross-channel and along-channel lengths both about 2 km. The Point extends as a submarine ridge down to the full depth of the Main Basin, in excess of 200 m at this location. There is a noticeable deepening of the channel bottom at the foot of the ridge, as there is in a number of locations throughout the Sound. This is likely due to a local increase in tidal current amplitude, resulting in less deposition of sediment. The walls of the channel, and the sides of the ridge, are extremely steep by oceanic standards, being on the order of 1:4 (vertical:horizontal).

To simulate tidal headland eddies at Three Tree Point we ran a numerical simulation using the Hallberg Isopycnic Model (Hallberg and Rhines 1996; Hallberg 2000). The model bathymetry was developed by Miles Logsdon as the University of Washington. We used just an 8 km by 8 km square section of the channel for the model domain (Figure 1). In order to have open boundaries on the domain ends we made the channel “re-entrant,” meaning that it is like a continuous loop; whatever leaves the north end comes back in the south end. This is a justifiable approximation because the stratification and tidal amplitude change little over this domain, and we are only simulating four tidal periods. Beyond this time the headland eddies tend to propagate beyond the edges of the domain. The model has a 100 m horizontal grid size, and 11 vertical layers, each with constant density (0.05 kg m^{-3} density step between layers). The layers, and the free surface, move up and down during the integration. The initial layer thickness is very thin near the top and much thicker near the bottom, giving a base stratification which matches the annual average from CTD casts at a nearby PSAMP station (data courtesy of Jan Newton, Washington State Dept. of Ecology). The deeper bottom boundary layers are poorly resolved in this simulation because the layers are too thick there. The model has parameterizations of internal mixing (based on the gradient Richardson number) and bottom friction (based on a quadratic drag law). The flow is forced by a barotropic body force which, in the absence of topography or friction, would give rise to a barotropic along-channel tidal current with amplitude 0.15 m s^{-1}, and M_2 tidal frequency (period = 12.42 hours, a "lunar hour"). The model is run for four tidal periods.

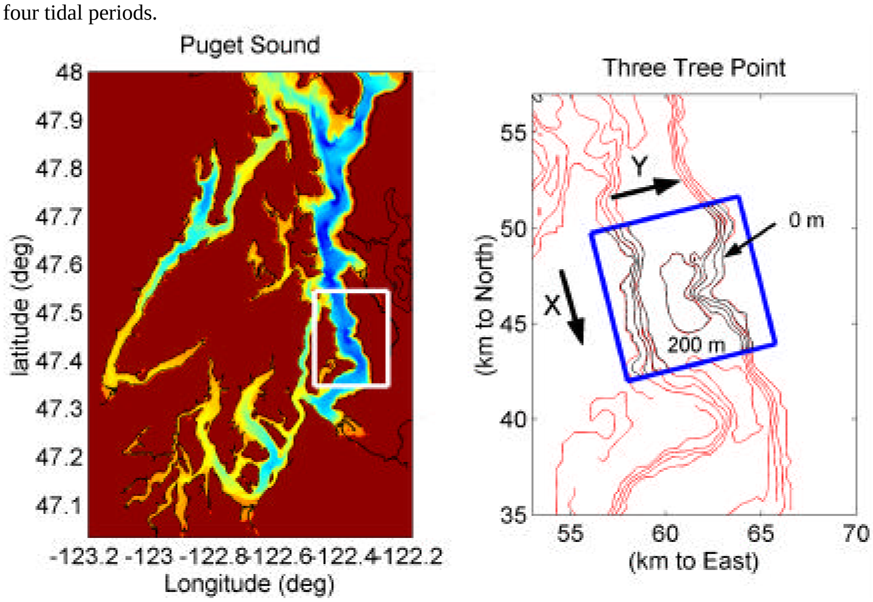

Figure 1. Bathymetry of the Puget Sound region, and domain for the numerical model. Three Tree Point is on the right side of the channel, in the middle of the tilted box in the right panel. The numerical model coordinate definitions (X,Y) are shown in the right panel. The model domain is 8 km square.

Model Results

Headland eddies form on both phases of the tide, and persist long enough to interact with each other (Figure 2). This long apparent long eddy lifetime is an important feature of deeper coastal flows, and may lead to much more effective tracer dispersion compared to shallow (~20 m) water. The eddy vortex cores are aligned with the slope of the Three Tree Point ridge, and so are progressively farther offshore as you go deeper.

Large isopycnal interface displacements are also predicted by the model (Figure 3). These have the form of trapped lee waves, or "mountain waves," and can be as large as 50 m for deeper water. The theory of MacCready and Pawlak (2001) predicts that for this ridge waves will develop in the deeper water, whereas flow is more likely to be nearly horizontal in the more stratified upper water. However, in the upper water the flow is also constrained by the free surface, and so must follow isobaths there, except for where it separates. This complex interplay of wave and eddy dynamics is a primary challenge for our understanding of the flow at such locations.

Tracer stripes were introduced in each layer, to study the Lagrangian stirring. The initial tracer field is shown in Figrue 4. After 1 tidal period (Figure 5, time shown is in lunar hours) stirring within one tidal excursion (2 km) of the Point is obvious. By two tidal periods (Figure 6) the headland eddies have caused significant stirring halfway across the channel, and several tidal excursions along the channel. Clearly these eddies can be a significant source of horizontal stirring. Their effectiveness is enhanced by the fact that they are long-lived, and may self-propagate.

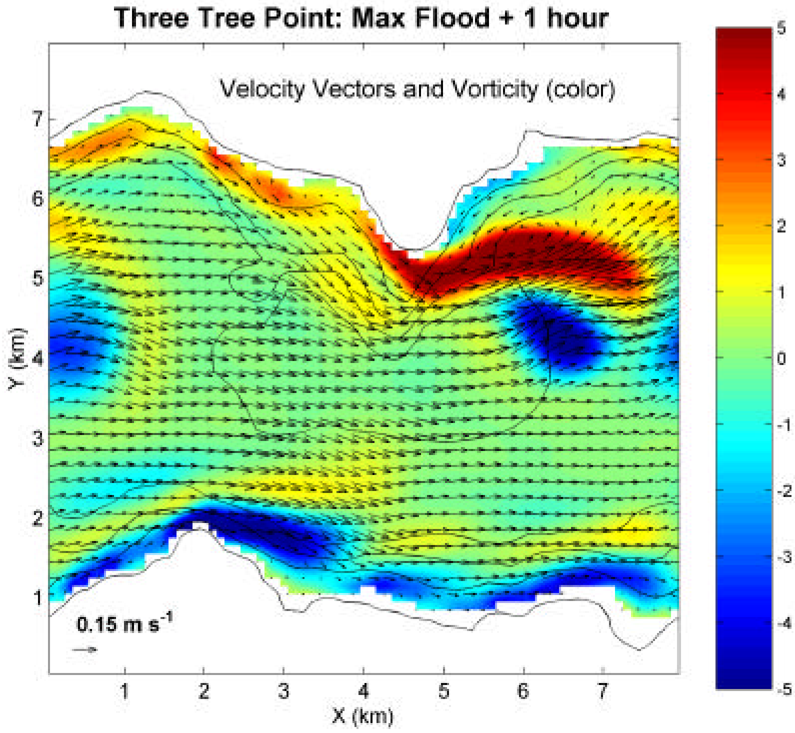

Figure 2. Plan view of velocity (arrows) and relative vorticity (color) in a near-surface layer of the numerical simulation. Bathymetry is shown with solid lines, going from 0 to 200 m in steps of 50 m. The time of this image is one lunar hour past maximum flood current (flood is to the right). Flow separates at the Point, and forms a strong cyclonic eddy (the red patch). The units of the vorticity field are 10^{-4} s^{-1}, and a patch of water with vorticity = $5x10^{-4}$ s^{-1} will rotate completely in about 7 hours. There is also a patch of negative vorticity offshore of the red patch. This is the remainder of the headland eddy formed on the previous ebb tide.

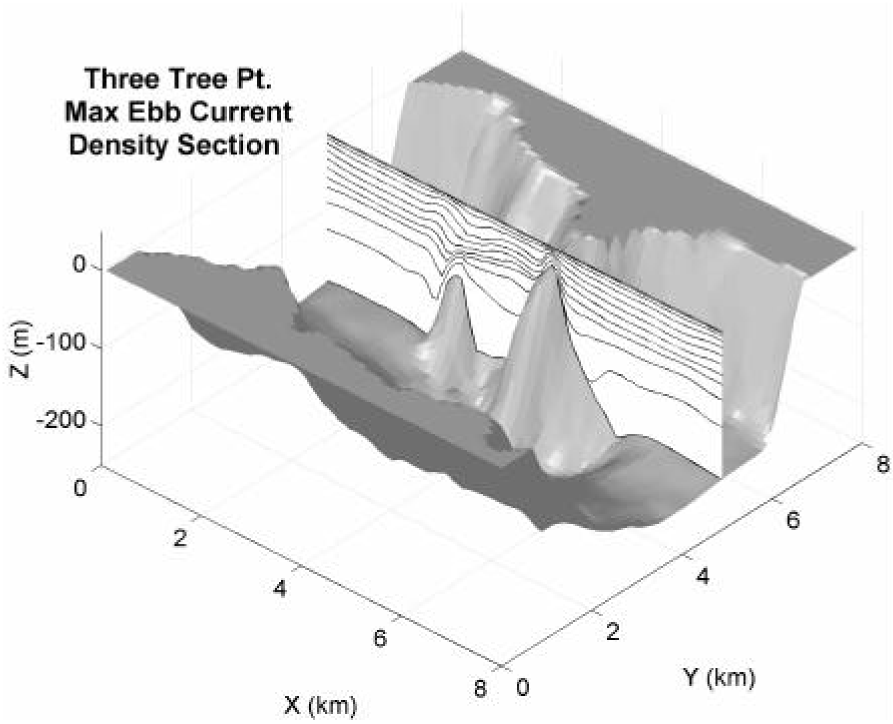

Figure 3. Model bathymetry and a section of isopycnals during max ebb current. Three Tree Point is the larger ridge coming from the upper right, and the current is flowing to the upper left. The isopycnal displacements are large, up to 50 m for the deeper water. The isopycnal displacements have the form of standing lee waves on this section. There is much less disturbance to the density field away from the Point.

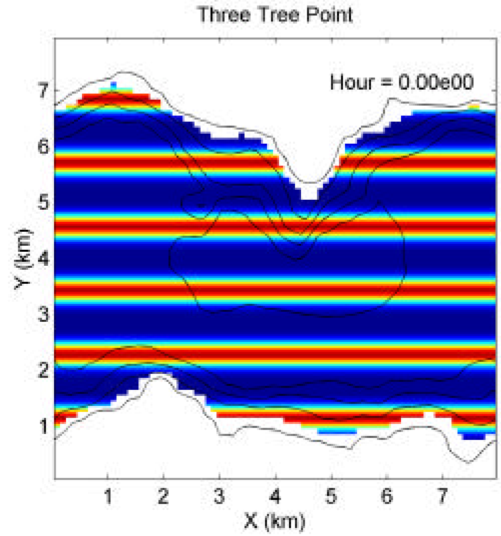

Figure 4. Plan view of the initial tracer distribution in a near-surface layer of the numerical simulation.

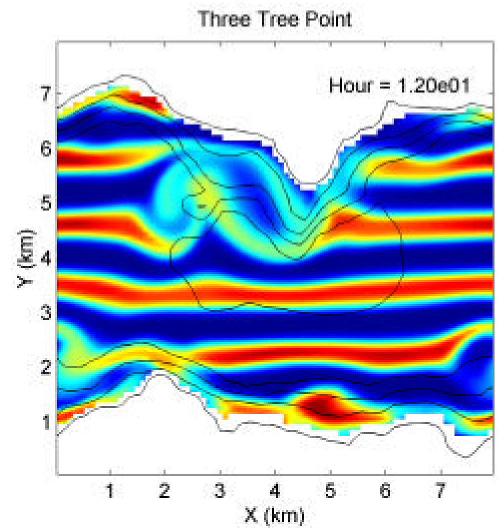

Figure 5. Plan view of the tracer distribution after one tidal period (12.42 hours, or 12 lunar hours). The stirring effect of the Three Tree Point eddies is apparent.

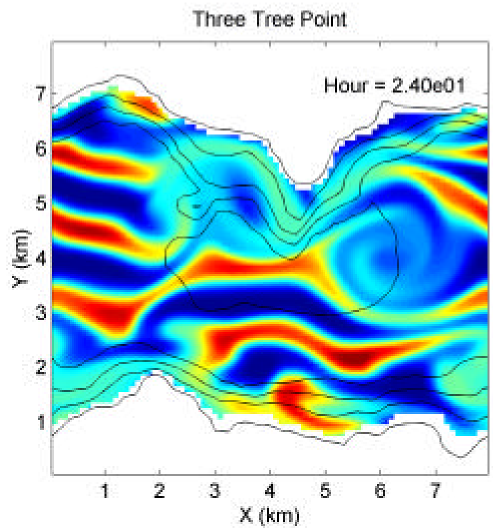

Figure 6. Plan view of the tracer distribution after two tidal periods (24 lunar hours). The eddies have now stirred fluid in a region about 2 km (across channel) by 5 km (along channel).

Conclusions

Interaction of tidal currents with Three Tree Point is predicted by our model to cause both strong internal waves and horizontal eddies. The eddies are long-lived because the water is deep. The eddies interact with each other, and rapidly stir tracer across the channel. We still have much to learn about such eddies in deep water. In particular:

- What is the effect of the trapped lee wave in the flow at depth?
- Is there enhanced mixing of nutrients up to the euphotic zone?
- Do the eddies really remain coherent over several tidal cycles, or are they torn apart by their complex vertical structure?

These questions are being explored observationally by the authors on a series of NSF-funded cruises to Three Tree Point in 2001 and 2002.

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